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ON THE EMISSION-LINE RESPONSE TO CONTINUUM VARIATIONS IN THE SEYFERT GALAXY NGC 5548

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ABSTRACT

Recently, two intensive optical monitoring projects were carried out, with the aim of measuring the continuum and emission line variations in the Seyfert galaxy NGC 5548. The two groups, observing the galaxy during two different periods, reported apparently contradicting results for the delay of Hβ variations with respect to the continuum. Using the UV measurements of Clavel *et al.*, obtained the same year as one of the above data sets, we show that the emission-line lag behind continuum variations depends on the continuum variability time scale in this object, in the sense that continuum variations with larger time scales give larger emission-line lags. Since the continuum variability time scales are different in the data sets obtained by the two groups, so are the derived lags. Such an effect can arise in some thick BLR geometries, especially if the line response to the ionizing flux changes is nonlinear. Using Monte Carlo simulations, we show that even without resorting to a nonlinear response, there is at least one possible model that could reproduce the two differing delays. In view of the effect, we note that previously reported differences in the lags of various emission lines are uncertain. In particular, we find that, using only the largest outburst in the simultaneous optical and UV light curves, Lyα, C IV λ1549, and Hβ all have similar lags behind the continuum.

Subject headings: galaxies: individual (NGC 5548) — galaxies: Seyfert

I. INTRODUCTION

A dramatic advance in the study of active galactic nuclei (AGNs), through observations of their emission-line variability, has taken place during the past year or so. This has come about as a result of the appearance of several new data sets which, for the first time, enable detailed studies of the size, structure, and dynamics of the so-called broad-line region (BLR) of several Seyfert 1 galaxies (Maoz *et al.* 1990; Netzer *et al.* 1990; Maoz *et al.* 1991; Clavel *et al.* 1991*a*; Peterson *et al.* 1991; Clavel *et al.* 1991*b*). A general review on the use of variability to map the emission line regions of AGNs, and a summary of observations up to 1988 is given by Peterson (1988). A summary of the present status of the field can be found in Osterbrock (1990).

In this *Letter* we address some previously unnoticed features of the recent ultraviolet observations of NGC 5548 and an apparent discrepancy between the results of two optical data sets for this source.

Netzer *et al.* (1990) monitored the optical line and continuum variability of NGC 5548 from the Wise Observatory in 1988. They detected a small, but clearly resolved, continuum pulse lasting about 40 days. The Hα and Hβ lines showed a response to this variation with a certain lag. Through a cross-correlation analysis, this lag was determined to be 7 days for Hβ. Through Monte Carlo simulations, they found that the uncertainty in this result was ± 3 days, assuming a thin-shell type BLR geometry of radius 7 lt-days for this object.

The following year (1989), NGC 5548 was again monitored intensively, this time by a large international collaboration. Clavel *et al.* (1991*a*) observed it in the UV every 4 days over an 8 month period using the *IUE* satellite, while Peterson *et al.* (1991) observed it at optical wavelengths from the ground. Again, through cross-correlation of the optical light curves and Monte Carlo simulations, Peterson *et al.* found Hβ lags the continuum by 19 days, with a small uncertainty of 2 or 3 days.

Thus, there is an apparent contradiction between the lag of 7 ± 3 days found by Netzer *et al.* (1990) and the lag of 19 ± 3 days found by Peterson *et al.* (1991) for the same emission line in the same object. However, we show below that there may be no real discrepancy between the two results, since the emission-line response time in NGC 5548 depends on the continuum variability time scale, and this time scale is different in the two data sets.

II. DISCUSSION

Figure 1 shows superposed the light curves of Clavel *et al.* (1991*a*) for the UV continuum and for Lyα. The light curves have been adjusted to the same vertical scale for an easy comparison of their temporal characteristics. Error bars are omitted for clarity's sake. The continuum displayed three main variability "events," to which we will refer as the first, second, and third events, according to their chronological order. The duration of each event is different: about 70, 100, and 50 days, for the first, second, and third events, respectively. It is also clearly apparent that the delay in the Lyα response to each event is different, in the sense that the delay is larger when the duration of the continuum event is longer.

These visual impressions are borne out by a cross-correlation analysis of each event separately. Set the first event to last from JD 7510 to 7582, the second from JD 7586 to 7689, and the third from JD 7692 to 7746. The full width at zero level of the autocorrelation functions of the three continuum events (giving a measure of the typical variation time scale) are, respectively, 35, 43, and 26 days. The cross-correlation functions of Lyα versus each continuum event have maxima at lags of 6, 16, and 3 days, respectively. These cross-correlation functions were calculated after interpolating the light curves to 1 day intervals. The maxima were found by fitting parabolas to the peaks of the cross-correlation functions. If we do not inter-

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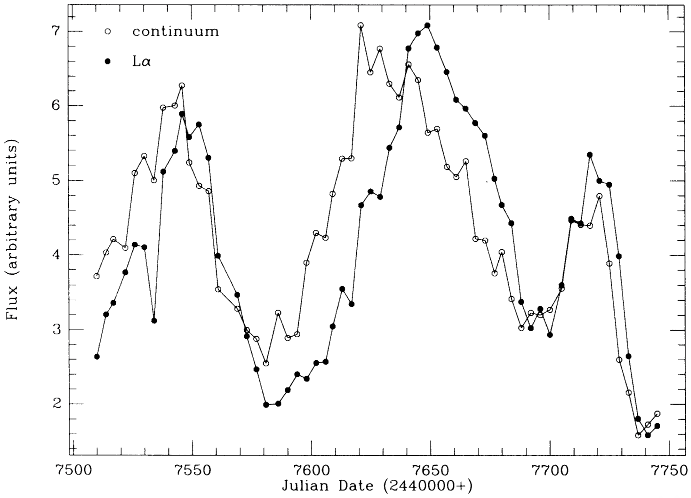

FIG. 1.—Light curves for the 1350 Å continuum and Lyα of NGC 5548, from Clavel *et al.* (1991*a*). The light curves are adjusted to have the same vertical scale. Error bars are omitted for clarity's sake. Note how the delay in the response of the emission line to each continuum event changes with the duration of the event.

polate, and simply calculate the cross-correlation at lags that are multiples of 4 days, the fitted maxima are at 6, 16.5, and 3 days, respectively.

To attach an uncertainty estimate to these numbers requires assuming a particular physical model, which we wish to avoid at this point. We note, however, that Clavel *et al.* (1991*a*) find only very small uncertainties, of 2 or 3 days at most, associated with the lags obtained from cross-correlating the entire time series.

The C IV λ1549 light curve from Clavel *et al.* (1991*a*) shows very similar behavior, both under visual inspection and under cross-correlation analysis. In the Hβ light curve of Peterson *et al.* (1991), the effect, if it exists, is not clearly discernible, since the ratio of variability amplitude to measurement error is smaller there. This, together with some gaps in the sampling, results in a blurring of the light curve, and in particular the last event. Nevertheless, cross-correlation of the Hβ light curve with each optical continuum event separately gives lags of 14 and 19 days for the first and second events, respectively, while no clear or significant peak exists for the third event. If, to improve the signal, we use the UV continuum light curve for the third event, we obtain a marginally significant cross-correlation peak at a lag of 2 days.

We have thus shown, at least for the two main UV lines, that the emission-line response time in NGC 5548 changes with the continuum variability time scale. For Hβ, the same trend may exist, but the evidence is not as conclusive. We note that the 10 day lag of the C IV λ1549 and Lyα lines behind the continuum, found by Clavel *et al.* (1991*a*), is *the average* of the lags we find for each event separately. Likewise, the lag of the Hβ line, found by Peterson *et al.* (1991), could be a weighted average of the three different events. Furthermore, considering only the second, and largest, event, there is no great difference between the lags of Hβ and the UV lines; cross-correlation shows that Hβ lags Lyα by only 4–5 days, and Hβ lags C IV λ1549 by 0–2 days. The range given in the position of the peak results from slightly different definitions of the "event" limits and the range of lags about the cross-correlation peak which are fitted to determine the maximum.

Returning to the discrepancy in the Hβ lag between the data of Netzer *et al.* (1990) and Peterson *et al.* (1991), the continuum pulse observed by the former lasted 40 days. The full width at zero level of its autocorrelation function is only 16 days. Given the behavior of the ultraviolet lines and the existence of a similar trend in Hβ, the small lag observed by Netzer *et al.* (1990) is to be expected.

It is well known that the peak of the cross-correlation function depends on the gas distribution, the line response, and the nature of the continuum light curve. A possible explanation for the case under study is the existence in NGC 5548 of a "thick" BLR geometry, where the ratio of outer to inner radius is $\gg 1$. The transfer function of such a geometry, relating the continuum and emission-line light curves, is generally peaked near zero lag and then monotonically decreasing at larger lags (see, e.g., Maoz *et al.* 1991). The cross-correlation function is the convolution of the continuum autocorrelation function with the transfer function. As a result, the peak of the cross-correlation function will be shifted to larger lags for broader continuum autocorrelations (i.e., for more slowly varying continua).

The effect can be further enhanced if the response of the lines to changes in the ionizing flux is nonlinear (which is probably the case, at least for some lines). In particular, the ionization level of the gas may be different at differing locations in the BLR. A change in the ionizing continuum level could then cause differing fractional changes in the local emissivity of a certain line at different BLR radii. The very different behavior of the C IV λ1549 and Lyα lines to continuum pulses of different durations and amplitudes is very suggestive of a nonlinear response.

The relevance of "thick" BLR transfer functions has been recently shown observationally by Maoz *et al.* (1991) for the case of the Seyfert galaxy NGC 4151. For NGC 5548, the transfer functions of the various emission lines have also been recently estimated (Krolik 1990; Horne, Welsh, and Peterson 1991). However, if the local emission-line response is nonlinear rather than linear, as all of these authors have assumed, then their derived transfer functions could be incorrect.

While a nonlinear response of the lines to continuum variations is likely to be relevant here, its detailed investigation is beyond the scope of this *Letter*. Instead, we show that the apparent discrepancy in the Hβ lag of NGC 5548 is entirely consistent even with a linear response of a thick BLR, given the two different continuum light curves.

We have carried out Monte Carlo simulations as described by Maoz and Netzer (1989). Model continuum light curves are created by linearly interpolating the continuum data of Netzer *et al.* (1990) and Peterson *et al.* (1991). Each of these are then convolved with the transfer function of a certain BLR geometry, to obtain model emission-line light curves. The continuum and emission-line light curves are then sampled at random the same number of days as was the case in each observed data set, and the appropriate measurement errors are added at random. The resulting simulated measurements are linearly interpolated, cross-correlated, and the lag found. Starting from the sampling of the model light curves, the process is repeated many times and the cross-correlation peak distribution (CCPD) is found. It gives the probability of obtaining any lag from cross-correlation of a particular data set, assuming the existence of a particular BLR geometry.

Figure 2 shows the two CCPDs, corresponding to the Netzer *et al.* and the Peterson *et al.* data, for a spherical BLR

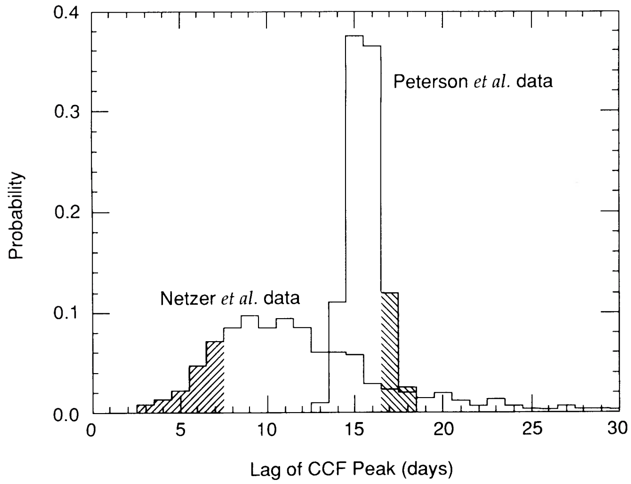

FIG. 2.—The cross-correlation peak distributions (CCPDs) calculated for a spherical BLR model of inner and outer radii of 2 and 60 lt-days, respectively, and pertaining to the data of Netzer *et al.* (1990) and Peterson *et al.* (1990). The CPPDs give the probability of obtaining some lag through a cross-correlation analysis of each of these data sets, assuming this BLR geometry. Note that the most likely lag is different in the two sets. The hatched area gives the probability of obtaining the lags actually reported by the two groups; note that both results are quite probable.

model of inner radius 2 lt-days and outer radius 60 lt-days. The effect explained above is clearly seen: with such a geometry, the most likely lag in the Netzer *et al.* data would be of 11 days, while in the Peterson *et al.* data, it would be 15 days.

Netzer *et al.* found an Hβ lag of 7 days. Cross-correlating the continuum and Hβ light curves of Peterson *et al.*, we find a lag of 17 days. (This differs from the lag of 19 days reported by Peterson *et al.* due to the slightly different cross-correlation algorithms used.) Due to the finite and uneven sampling and the measurement errors, the CCPDs have a certain width. As a result, there is a 17% probability of obtaining a lag of 7 days or less for the Netzer *et al.* continuum variability pattern, and a 14% chance of observing a lag of 17 days or more for the Peterson *et al.* pattern. Thus we have shown that there is at least one model that would give the two different observed lags with reasonable probability. As mentioned earlier, nonlinearity would most likely increase the discrepancy in this and similar geometries.

While these results are suggestive of the BLR geometry that may be relevant in NGC 5548, a clearer determination will result from a more sophisticated analysis of the measurements of the various emission lines combined with photoionization modeling. Such an analysis will be described elsewhere. Here, we have shown that the results from two separate AGN monitoring projects do not contradict, but rather could be showing the same effect. This, and the response of the ultraviolet lines to the different parts of the continuum light curve, may be revealing important details about the structure of the BLR in NGC 5548.

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